Electron loss and capture by fast helium ions in noble gases

N. V. de Castro Faria, F. L. Freire, Jr., and A. G. de Pinho
Departamento de Física, Pontifícia Universidade Católica do Rio de Janeiro (PUC/RJ), 22 453 Rio de Janeiro, Rio de Janiero, Brazil
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We have measured charge-changing cross sections with He^+ and He^{2+} ions impinging upon target gases He, Ne, Ar, and Kr. The energy range of the helium ions was 0.75–4 MeV and the cross sections were obtained either by the initial-growth method or by the attenuation method. The measured values were compared with the corresponding cross sections obtained with equal velocity H^+ and H projectiles. Deviations from the simple scaling rules usually applied to the capture process are discussed.

In a recent publication[1] we reported one- and two-electron capture and/or loss cross sections of ionic (H^+,H^-) and atomic hydrogen species impinging upon noble gases (He,Ne,Ar) within the velocity range $3 \lesssim v \lesssim 12$ (atomic units, $v_0 = \alpha c$, will be used). Many regularities were observed, such as, e.g., the conspicuous behavior of the three capture cross sections from Ar, where a remarkable structure[1–3] is present which is related[4] to the transition from the dominant *M*-capture regime to the *L*-capture regime as v increases. The use of scaling rules derived from the simplest first-order treatment of the one-electron capture[4] and the assumption that the two electrons are captured independently lead to a successful description of the double-capture experimental results.[1] A natural extension of that work was the investigation of the corresponding processes with helium ions (He^+ and He^{2+}). The dependence of the cross sections on the projectile charge deserves particular attention and we are now able to compare one-electron capture by H^+, H, He^+, and He^{2+}, and two-electron capture by H^+ and He^{2+} with projectiles of equal velocity.

$^4He^+$ and $^4He^{2+}$ beams from the 4MV Van de Graaf accelerator at Pontifícia Universidade Católica do Rio de Janeiro were used to determine the cross sections for electron loss (σ_{12}), one-electron capture (σ_{10} and σ_{21}), and two-electron capture (σ_{20}) from He, Ne, and Ar. The σ_{12} cross section for Kr was also measured.

Data available in the literature for impact energies above 1.5 MeV are relatively scarce. Pivovar *et al.*[5] measured the cross sections σ_{12} and σ_{10} for He and Ar in the energy interval 0.2–1.5 MeV. We have extended these measurements up to 4 MeV, starting at 0.75 MeV; and data for Ne are reported for the first time. Values of σ_{21} were measured by Hvelplund *et al.*[6] in the energy range 1–7 MeV for He and Ar, by Pivovar *et al.*[7] from 0.3–1.5 MeV, and by Shah and Gilbody[8] for He targets and energies ranging from 0.2–2.4 MeV. These last authors have shown that transfer double ionization and autoionizing double capture can also contribute to the production of He^+ from He^{2+} beams impinging upon He targets. In the experiments reported here and in Refs. 6 and 7 these processes are not distinguishable from each other. Selective capture from the Ne *K* shell by He^{2+} was measured by Rödbro *et al.*[9] Double-capture cross sections above 1.5 MeV are not available in the literature. One can find two values of σ_{20}, at 1.0 and 1.4 MeV, for the He^{2+}-He system[10] and systematic measurements by Pivovar *et al.*[7] in the 0.3–1.5 MeV interval for He and Ar among other gaseous targets.

Theoretical calculations for one-electron capture follow different approaches: (i) the first-order perturbation theory of Oppenheimer-Brinkman-Kramers (OBK) extended to multielectron target atoms by Nikolaev,[4] which is the simplest one; (ii) the continuum-distorted-wave (CDW) approximation;[11] and (iii) the strong-potential Born (SPB) approximation including the additional peaking approximation.[12] More recently,[13,14] the first-order Born approximation was reexamined with great success. Deco *et al.*,[15] using the symmetric eikonal approximation, succeeded in giving the description of the experimental data for the total cross section for one-electron capture by He^{2+} incident on helium. It is worthwhile mentioning that their calculated σ_{21} cross section is a lower limit, to be compared with the experimental results. In fact, experimental observations do not distinguish the final state of the target and they assumed that the target is left in the 1*s* state. Double electron capture by fast nuclei was calculated by many authors[16–20] within different approximations, but the emphasis was often on collisions with helium atoms. Another approach used to describe both single- and double-capture processes by helium ions is based on the binary-encounter approximation.[21–24]

Special care must be taken when $^4He^{2+}$ ions produced in a rf ion source are accelerated because the beam is heavily contaminated with $H_2{}^+$ molecular ions since they have almost identical values of ME/q^2. To circumvent this inconvenience, beams of $^4He^+$ were accelerated to an energy E and then were sent through a gaseous stripper at a pressure around 100 mTorr before entering the analyzing magnet. Doubly charged ions of the same energy E were produced in the stripper and the contamination with protons of the same energy was always less

TABLE I. Cross section for electron loss σ_{12} (in units of 10^{-17} cm^2).

E (MeV)	He	σ_{12} (10^{-17} cm^2) Ne	Ar	Kr
0.75		5.26	12.4	13.0
1.0	1.60	6.04	14.1	15.2
1.2	1.34	6.03	13.0	15.7
1.5	1.20	6.03	12.5	17.0
2.0	0.93	5.90	11.7	16.6
2.5	0.86	5.31	10.4	16.1
3.0	0.76	4.89	9.6	15.5
3.5	0.66	4.50	9.2	14.7
4.0	0.59	4.08	8.7	13.6

than 1%. The target gases are claimed by the manufacturers to be 99.99% pure. However, it was necessary to feed He into the target cell through a copper tube cooled by liquid nitrogen in order to remove condensable impurities.

Details of the experimental setup are presented in Ref. 1. The target chamber was a differentially pumped gas cell where the pressure could be varied from 2–200 mTorr. A pressure differential of nearly 1000:1 was obtained. Pressures in the gas cell were monitored with a thermocouple calibrated for each gas against a McLeod gauge. The pressure in the rest of the system was kept lower than 10^{-6} Torr. The switching magnet was used as the charge analyzer of the beam emerging from the collision chamber, the resulting charge components being simultaneously collected by Faraday cups provided with secondary electrons suppressors. Before entering the cup the neutral beam went through a biased aluminum-coated Mylar foil, becoming an equilibrated beam whose effective charge was determined from the equilibrium fractions. The negatively charged component was neglected in this experiment. The distance from the target to the detection system was about 1.5 m. The cross sections were obtained either by the growth-rate or by the attenuation method.

Tables I and II summarize our results for the loss and the capture cross sections, respectively, for the different target gases. An average uncertainty of 10% must be assigned to the absolute values of the cross sections measured in this work. The main sources of experimental errors are the target thickness determination and the fitting procedure, to extract the cross section from the measured charge fractions. The uncertainties in the ratios of nearby cross sections are estimated to be typically $\frac{2}{3}$ of those of the absolute cross sections.

For equal-velocity projectiles with $v \gtrsim 4.5$ the ratio of the one-electron–loss cross sections for atomic hydrogen and for He^+ is approximately v independent and assumes the same numerical value, $\sigma_l(H)/\sigma_l(He^+) \simeq 2.15$, for Ne and Ar targets. This number is not very different from 2, as predicted by Bohr[25] for intermediate values of Z_2. For the helium target this ratio is larger and exhibits a slight dependence on the velocity. The $\sigma_{12}(v)$ function presents a broad maximum which was firstly observed experimentally by Pivovar *et al.*[5] In the present experiment the maximum occurs at lower velocities for the lightest targets but is very well characterized for Kr. For the highest velocities the ratio of σ_{12} for the different targets is roughly v independent and it is possible to investigate the dependence on the target atomic number. The free-collision approximation of Bohr[25] predicts a dependence on Z_2 which becomes increasingly weak as Z_2 increases. Going from Ar to Kr it was found to be $\sim Z_2^{0.6}$, and for the triad He-Ne-Ar, it is $\sim Z_2^{1.2}$.

The most significant discrepancy between our measured values and those previously published by other authors occurs for the σ_{21} cross section for He. In this case our values are systematically 30–40% lower than those reported in Refs. 6 and 8, a difference that goes beyond the quoted combined systematic error of the experiments. Having ascertained this difference at the very beginning of our experiment, several more measurements of σ_{21} were made, for different values of the energy, for the duration of the experiment. The results quoted in Table II are thus the mean of independent measurements which never differed by more than 15% from one another. We do not understand the basis for these discrepancies at the present time. The present results as well as the previous ones are consistent with the lower limits calculated by Deco *et al.*[15] for σ_{21}.

A Z_1^5 scaling law is usually invoked in connection with the one-electron capture process. It is important to notice that it results from the product of a Z_1^3 factor related to the final state of the projectile by a Z_1^2 factor coming from the interaction between the incoming particle and the active electron. The relation $Z_1 \ll Z_2$ which provides the condition justifying this scaling rule is the

TABLE II. Cross section for one-electron capture (σ_{21} and σ_{10}) and two-electron capture (σ_{20}) (in units of 10^{-21} cm^2).

E (MeV)	σ_{21} (10^{-21} cm^2) He	Ne	Ar	σ_{10} (10^{-21} cm^2) He	Ne	Ar	σ_{20} (10^{-21} cm^2) He	Ne	Ar
1.2	6830	38 300	17 300	1150	5400	1800	31.0	597	97.4
1.5	3000	22 500	9590	520	3000	960	8.3	243	70.9
2.0	1040	9800	5660	187	1320	440	0.82	54.5	43.0
2.5	400	4630	4170	76	644	280	0.25	12.2	25.1
3.0	200	2500	3190	39	348	209	0.065	5.57	14.3
3.5	110	1400	2380	21	210	168		2.28	7.65
4.0		917	1900	12	134	135		0.85	5.40

basic assumption in the SPB description of K-K capture and, in this case, it implies a similar relation for the binding energies of the active electron, viz., $\varepsilon_1 \ll \varepsilon_2$. In the Nikolaev version of the OBK approach[4] this scaling rule results from an approximate treatment of the factor

$$\gamma_1=[v^4+2v^2(\varepsilon_2+\varepsilon_1)+(\varepsilon_2-\varepsilon_1)^2]/4v^2 , \qquad (1)$$

which consists in considering $\varepsilon_1 \ll \varepsilon_2$ (ε_i and v are expressed in atomic units) implying that γ_1 no longer depends on the projectile. However, when $Z_2 \gg Z_1$ and the capture is from an outer shell of the target atom to the K shell of a light projectile like He^{2+} it may happen that ε_1 is no longer negligible relative to ε_2. If only one outer shell contributes significantly to the capture process an approximate scaling can be obtained which includes the residual dependence on the projectile present in the γ_1 factor. For example, $\sigma(He^{2+}\rightarrow He^+)/\sigma(H^+\rightarrow H)=[2\phi(v)]^5$, where

$$\phi(v)=\frac{\gamma_p}{\gamma_\alpha}=\frac{(v^2+\varepsilon_2+1)^2-4\varepsilon_2}{(v^2+\varepsilon_2+4)^2-16\varepsilon_2} . \qquad (2)$$

In the following, only the neon data will be discussed because in the 3.5–6.5 velocity interval only the L shell contributes to the capture process. In this same interval, M and L electrons contribute to the capture cross sections in Ar, being responsible for the same shoulder observed in the equal-velocity H^+ and H single- and double-capture cross sections. This shoulder appears now in the σ_{21}, σ_{10}, and σ_{20} cross sections. On the other hand, the helium data do not seem appropriate for a discussion in the framework of the OBK approximation.

The average value of ε_2 for the L shell of Ne is 2.09. The experimental ratio is compared with the predictions of Eq. (2) in Fig. 1(a). The experimental ratio is very far from the asymptotic ($v \gg 1$) value and its v dependence is satisfactorily reproduced.

The double capture can be considered in the same spirit as in Ref. 1, assuming that the electrons are captured independently. Then $\sigma_{20}=k\gamma Z_1^{*6}\sigma_{21}^2$ with $k=2.6\times 10^{12}$ when the cross sections are expressed in cm^2. Figure 1(b) shows the experimental values of $\sigma_{20}/k\sigma_{21}^2$ compared with γZ_1^{*6}, where γ is calculated for the capture from the L shell of Ne to the 1s state of He^+ and $Z_1^*=1.646$. This effective charge is obtained with the same criterion adopted in Ref. 1 to choose the effective charge of the $1s^2$ state of a two-electron system.

A more stringent test is the analysis of the ratio $\sigma(He^{2+}\rightarrow He)/\sigma(H^+\rightarrow H^-)$ since effective charges in both two-electron systems will be involved. Moreover, a more pronounced v dependence is expected. Figure 1(c) compares the experimental values of this ratio with its predicted value $16(1.646/0.582)^6\phi^9$ showing an excellent agreement, especially if one considers that the He atom can be formed in excited states not considered in the above estimates and that they can contribute with about 20% of the total cross section.

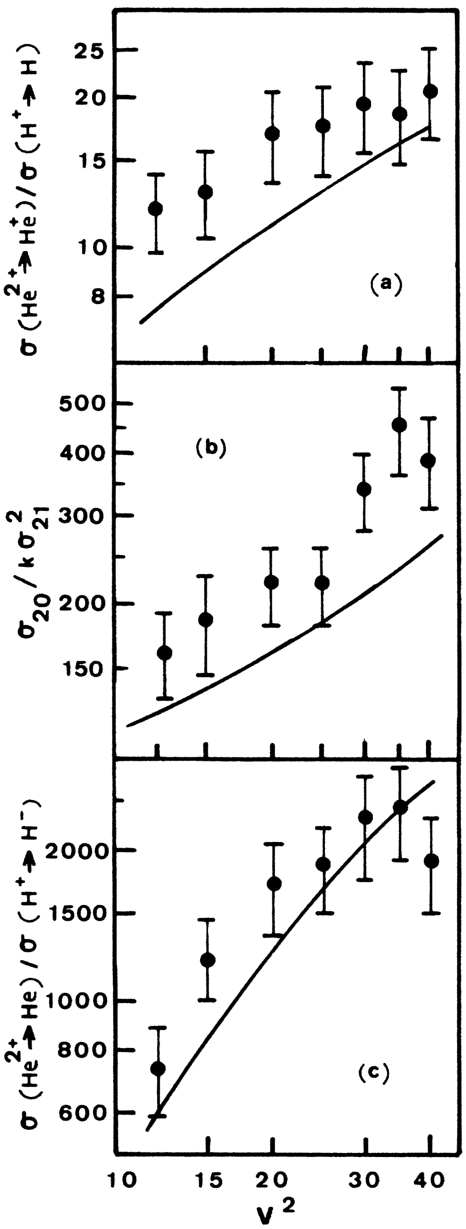

FIG. 1. Cross-section ratios for Ne compared with predictions based on the modified scaling rules (see text for explanation of the solid lines). (a) One-electron capture by He^{2+} and H^+; (b) one- and two-electron capture by He^{2+}; (c) double capture by He^{2+} and H^+.

Therefore it seems that the H and He data in the considered velocity range can be scaled with modified OBK scaling rules even for the double-capture process. The study of electron capture by heavier bare nuclei will be a very interesting test for these scaling rules.

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